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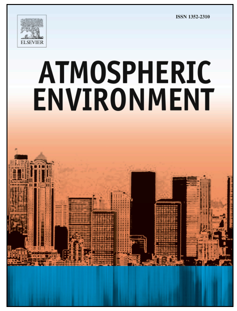

Black carbon emissions from flaring in Russia in the period 2012-2017

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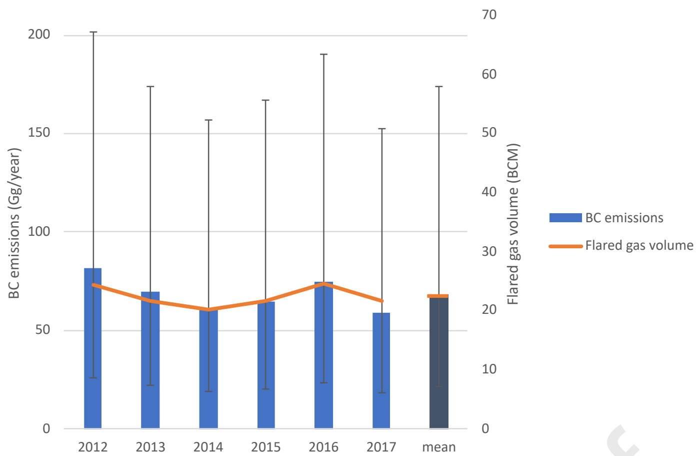
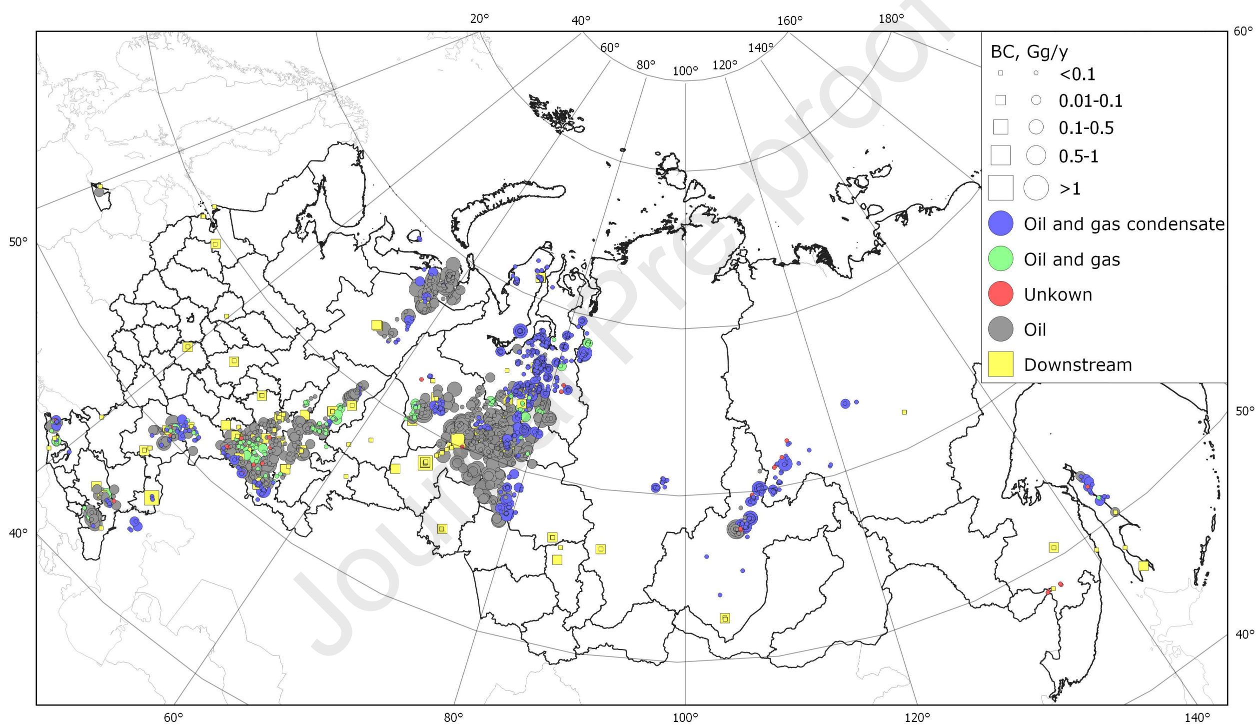

BC emissions (Gg/year)
Flared gas volume (BCM)
BC emissions
Flared gas volume
2012
2013
2014
2015
2016
2017
mean


BC, Gg/y
<0.1
0.01-0.1
0.1-0.5
0.5-1
>1
Oil and gas condensate
Oil and gas
Unkown
Oil
Downstream

Black carbon emissions from flaring in Russia in the period 2012-2017

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Highlights

- New estimate for black carbon emissions from flaring in Russia
- Enhanced temporal profiles of flared gas volume from VIIRS
- Oil and gas field-type specific emission factors developed
- Average BC emissions from 2012 to 2017 are estimated at 68.3 Gg/year

Abstract

Gas flaring in the oil and gas industry has been identified as an important source of anthropogenic black carbon (BC) affecting the climate, particularly in the Arctic. Our study provides, for the first time, spatially-explicit estimates of BC emissions from flaring in Russia utilising state-of-the-art methodology for determining the emission factors. We utilised satellite time series of the flared gas volume from Visible Infrared Imaging Radiometer Suite (VIIRS) for the period 2012 to 2017, supplemented with information on the gas and oil field type. BC emissions at flaring locations were calculated based on field type-specific emission factors, taking into account different gas compositions in each field type. We estimate that the average annual BC emissions from flaring in Russia were 68.3 Gg/year, with the largest proportion stemming from oil fields (82%). We observed a decrease in the yearly emissions during the period 2012 to 2017 with regional differences in the trend. Our results highlight the importance of detailed information on gas composition and the stage of oil and gas separation of the flared gas to reduce uncertainties in the BC emission estimates.

Graphical abstract

1 Introduction

Gas flaring is the burning of associated petroleum gas (APG) in the oil extraction industry. Although APG is a form of natural gas and can be utilised correspondingly after being processed, it is often flared instead (IEA, 2019). According to satellite estimates, globally about 145 billion cubic meters (BCM) of gas was flared in 2018 (The World Bank, 2019) corresponding to 350 million tons of CO_2 equivalent emissions per year. During flaring, air pollutants, such as black carbon (BC), SO_2, NO_X and CO, are released to the atmosphere, influence the Earth's radiative balance and can have a warming or cooling impact on climate (AMAP, 2015; Shindell et al., 2012). In the Arctic, BC is considered as a key pollutant inducing positive climate forcing (Bond et al., 2013). BC affects the Arctic climate via several mechanisms: (i) the atmospheric burdens contribute to direct heating of air, (ii) the deposition and concentrations in snow and ice reduce the surface albedo and accelerate the melting processes (Hadley and Kirchstetter, 2012) and iii) BC as a component of aerosols interacts with clouds (Bond et al., 2013; Kühn et al., 2020), affecting their formation, distribution, size and radiative properties (Boucher et al., 2013). Several studies have suggested that BC from flaring can be a significant factor contributing to Arctic warming (AMAP, 2015; Cho et al., 2019; Sand et al., 2016). BC emissions from flaring are estimated to account for about one third of emissions north of 60˚N and two thirds north of 66˚N; the emissions occur mostly in oil fields in the Russian territory (Stohl et al., 2015; Stohl et al., 2013). BC measurements on a ship campaign in the Arctic Ocean, complimented with simulated concentrations, showed that major flaring sites have a significant impact on local BC concentrations in the Arctic (Popovicheva et al., 2017).

According to the World Bank (2019), the amount of gas flared in 2018 in Russia was 21.3 BCM. Russian oil resources are mainly located in West Siberia and the Urals-Volga region. The largest oil producing region, accounting for 45% of the production in 2016, is the Khanty-Mansiysk area located in West Siberia. In 2016, about 12% of oil was produced in East Siberia and Russia's Far East (U.S. Energy Information Administration, 2017). Estimates of Russian BC emissions from anthropogenic sources indicate flaring of APG as the largest source sector, with the other main sectors being transport, agricultural waste burning and residential combustion (Evans et al., 2017; Huang et al., 2015; IIASA, 2020; Klimont et al., 2017). The contribution of flaring to the Russian total BC emissions has been estimated at 36% (Huang et al., 2015) or 46% (Conrad and Johnson, 2017). The emission estimates are burdened with uncertainties due to lack of, for example, emission measurement data from Russian flaring sites as well as missing facility-level activity data (see e.g. Huang et al. (2015)).

Satellite remote sensing provides information that can be used to derive spatial distribution and trends of gas flaring worldwide, including the Arctic. The satellite detection of flares is based on their radiative emissions. Currently, no instrument exists that was specifically designed for the detection of flares. In most cases, night-time images from medium resolution instruments, such as the Visible Infrared Imaging Radiometer Suite (VIIRS) (Elvidge et al., 2016; Zhang et al., 2015), the Along Track Scanning Radiometer (ATSR/AATSR), the Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) (Casadio et al., 2012; Caseiro et al., 2020; Caseiro et al., 2018) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Anejionu et al., 2015; Faruolo et al., 2018) have been utilised for the mapping of gas flares. All these instruments measure in the wavelength range of peak radiant emissions of flares at about 1.6 µm (Elvidge et al., 2016; Fisher and Wooster, 2018). Due to the moderate spatial resolution of the satellite observations, flares cover, in fact, only a small fraction of the pixel's footprint (~500 m^2 to ~1 km^2).

Globally consistent estimates of annual flared gas volumes have been made from VIIRS since 2012 (Elvidge et al., 2016). For this, the satellite estimates have been calibrated against country-reported data on gas flaring (Elvidge et al., 2016). These VIIRS-based estimates are utilised for the reporting of the amount of gas flaring by the World Bank's Global Gas Flaring Reduction Partnership (The World Bank, 2020). VIIRS Nightfire products showed better suitability for the detection of flares than the MODIS thermal anomaly products in Khanty-Mansiysk, Russia (Sharma et al., 2017). Furthermore, the derived flare source area from the VIIRS Nightfire algorithm correlated well with interpretations of Google Earth imagery (Sharma et al., 2017). Good accuracy of VIIRS Nightfire flared gas volume at offshore sites compared to reported values was found by Brandt (2020).

While remote sensing has been utilised to detect flaring locations and to provide estimates on the source temperature, the radiant heat and gas volume of the observed flares (Caseiro et al., 2018; Elvidge et al., 2016), emission factors are usually applied to convert the activity data (such as the flared gas volume) to emissions (Klimont et al., 2017). The BC emissions depend on the composition of the APG and the combustion process (Bond et al., 2004), which is affected, for example, by wind speed and the operating conditions of flares (exit velocity, flare size and tip design) (Evans et al., 2017; Huang et al., 2015; McEwen and Johnson, 2012). Detailed information about the emission factors is scarce, and can be based on laboratory measurements (McEwen and Johnson, 2012) or field measurements (Conrad and Johnson, 2017). This data is very limited, since it is only based on a small number of individual flares (Johnson et al., 2013) or from a flaring region (Gvakharia et al., 2017). Recently, satellite methods are also advancing towards the estimation of fire combustion efficiency, e.g. the potential for detection of the combustion phase of fires from VIIRS was shown by Wang et al. (2020).

Our objective was to calculate black carbon emissions from flaring in Russia based on satellite observations from VIIRS for the period 2012-2017. In this study, spatially-explicit information on the type of field was used for the first time to improve black carbon emission estimates from flaring. In addition, gas composition data of the APG in Russia was collected from the literature for different field types and applied together with the revised emission factor function from Conrad and Johnson (2017). We characterise spatial and interannual variability and BC emissions of flaring in Russian oil and gas fields. Furthermore, we derive uncertainty ranges for the estimated black carbon emissions and compare our results to the reported values in the literature.

2 Material and methods

An overview of datasets used and analysis conducted for estimating BC emissions in Russia is presented in Figure 1. Details of the methods are described in the following sections.

Figure 1. Flowchart of datasets and analysis steps for the estimation of black carbon emissions.

2.1 Satellite observations of flared gas volume

We utilised satellite-observed flared gas volume from VIIRS Nightfire data that are available at the Colorado School of Mines (https://payneinstitute.mines.edu/eog/) for the period 2012- 2017. The data are open source and readily available. The radiant heat (RH) of flares was derived from estimated flare temperature and source area using the Stefan–Boltzmann law. The subpixel flare source area was derived based on Planck Curve (Elvidge et al., 2016). The yearly sum of RH for all gas flares in the country obtained with VIIRS Nightfire was used to calibrate a linear regression versus the annually reported flaring volumes from Cedigaz (Elvidge et al., 2016). This calibration against country level flared gas volume was then re-distributed back between individual flares in the oil and gas fields according to the flare annual RH estimate. For 2012, the VIIRS Nightfire data covering the period April-December were extrapolated to obtain annual estimates of RH.

may be recognised according to the type of engineering facility (available in Rosreestr (Federal Service for State Registration Cadastre and Cartography of Russia) (2011)) or (Wikimapia)).

2) Major oil and gas companies usually present the levels of production per major fields. This information may be available online (e. g., the Novatek company presents production and reserves info on its official website: http://www.novatek.ru/en/business/producing) or reported in annual reports (e.g., Rosneft not only presents the production rates in their annual reports (Rosneft), but in the last years, the volumes of flared APG by the main subsidiaries are presented).
3) Other cartographic sources that may contain additional supportive information, such as the Hydrocarbon Province Maps of Russia (Blackbourn Consulting), Harvard Oil & Gas Maps (Harvard University) and GIS Atlas “Subsoil of Russia” (A. P. Karpinsky Russian Geological Research Institute (VSEGEI)) were used.
4) If there was no information found via the mentioned methods, any available information on the field production rates or deposits was looked up on the internet. Sometimes the information may be presented in mass media (oil and gas specialised sources or regional media), in scientific research papers (primarily on geology) of the fields, or in annual reports on the economic activity of the region.
5) If there was still no metadata found about the flare, its type is marked as ‘Unknown’.

The above methodology is based primarily on open-source data. To our knowledge, there is no single open-source table with information on oil and gas field classification available in Russia.

The observed gas flares were divided into upstream and downstream (Elvidge et al., 2018). Upstream flares are located at the oil and gas fields, i.e. close to the production sites. Downstream flares are related to processing plants and sites. We merged gas and gas condensate fields with the class oil and gas condensate field into one category.

BC emission factor for upstream flares, we utilised the range of emission factors for the specific field types (Table 2). For downstream flares, we applied the range of the calculated emission factors from all available gas composition data in Russia (0.19 – 12.17 g/m^3, Supplementary materials, Table S1). Thus, we estimated the lower bound of the uncertainty range in BC emissions by applying the lower bound of the flared gas volume and the minimum of the emission factor by field type. The upper bound of the uncertainty range was derived accordingly by using the upper bound of the flared gas volume and the highest emission factor for the respective field type.

3 Results

From 2012 to 2017, the annual average BC emissions from Russian flaring were 68.3 Gg/year, with 64.1 and 4.2 Gg/year from upstream and downstream flares, respectively. There was a slight decreasing trend in the annual emissions (Figure 2), but variation was high, as the highest emissions were for 2012, 81.4 Gg/year, and the lowest for 2017, 58.9 Gg/year. The uncertainties in BC emissions ranged from 21.13 to 148.79 Gg/year for upstream and from 0.33 to 24.93 Gg/year for downstream flares for the average period 2012 to 2017 (Table 3). Most emissions came from flares in oil fields (Figure 3), representing 82% of the emissions on average, although comprising only 32% of the number of flares (Table 1) and 41% of flared gas volume. Oil and gas condensate represented 10% of the emissions and 45% of flared gas volume, oil and gas 2%, and 6%, and downstream flares 6%, and 8%, respectively. From 2012 to 2017, the emissions decreased by a higher percentage than the flared gas volume. This is due to flared gas volumes decreasing in oil fields. The flaring volumes from oil and gas condensate fields were highest in 2016 and 2017 and showed an increasing trend. As the emission factor was significantly lower in oil and gas condensate fields than in oil fields, the oil fields drove the changes in the emissions.

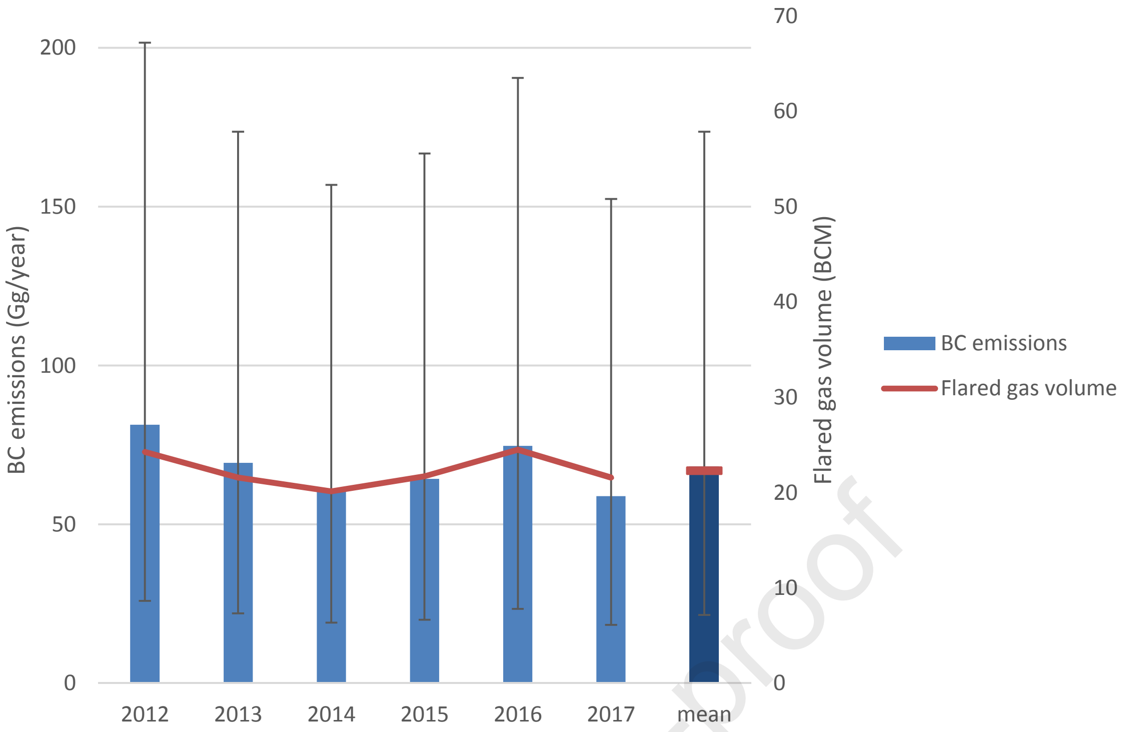


Figure 2. Annual black carbon emissions with uncertainty ranges from Russian flaring and volume of the gas flared.

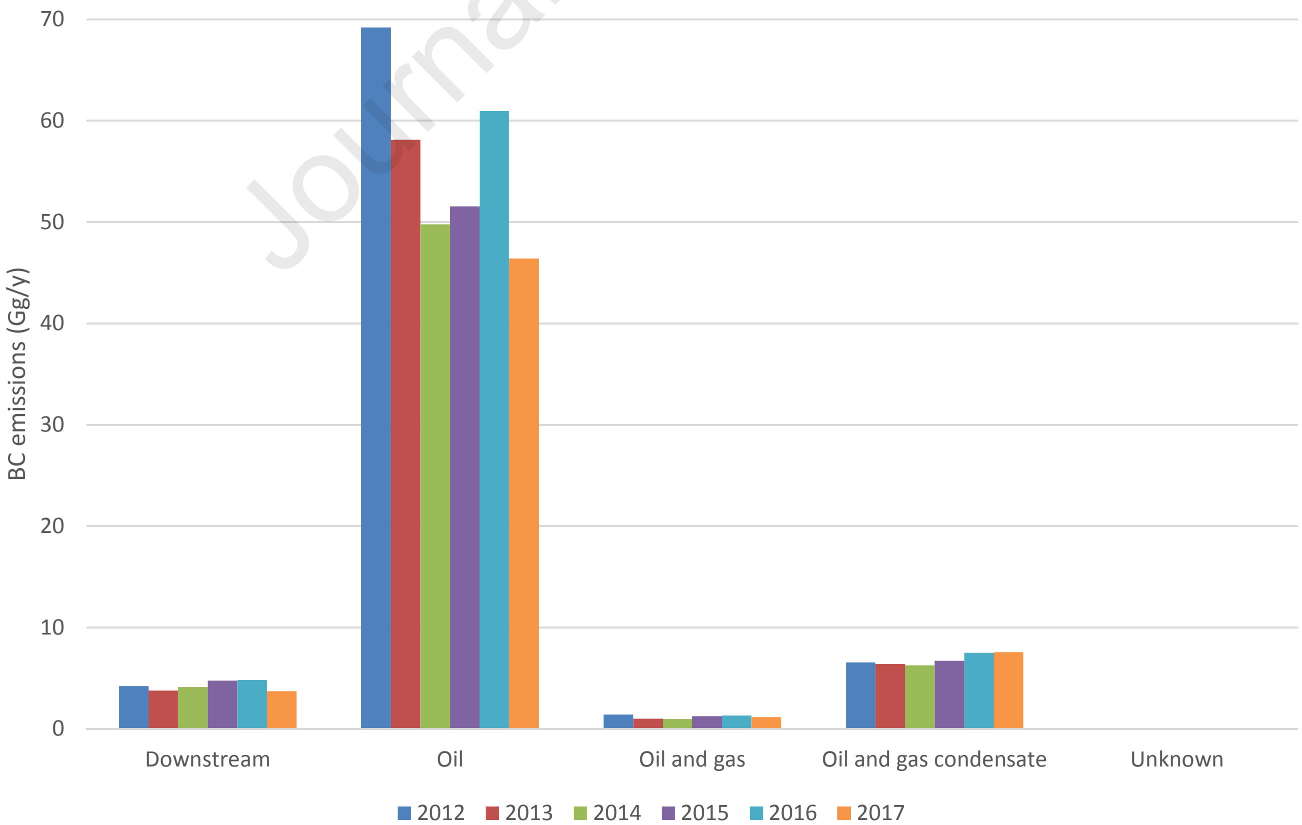
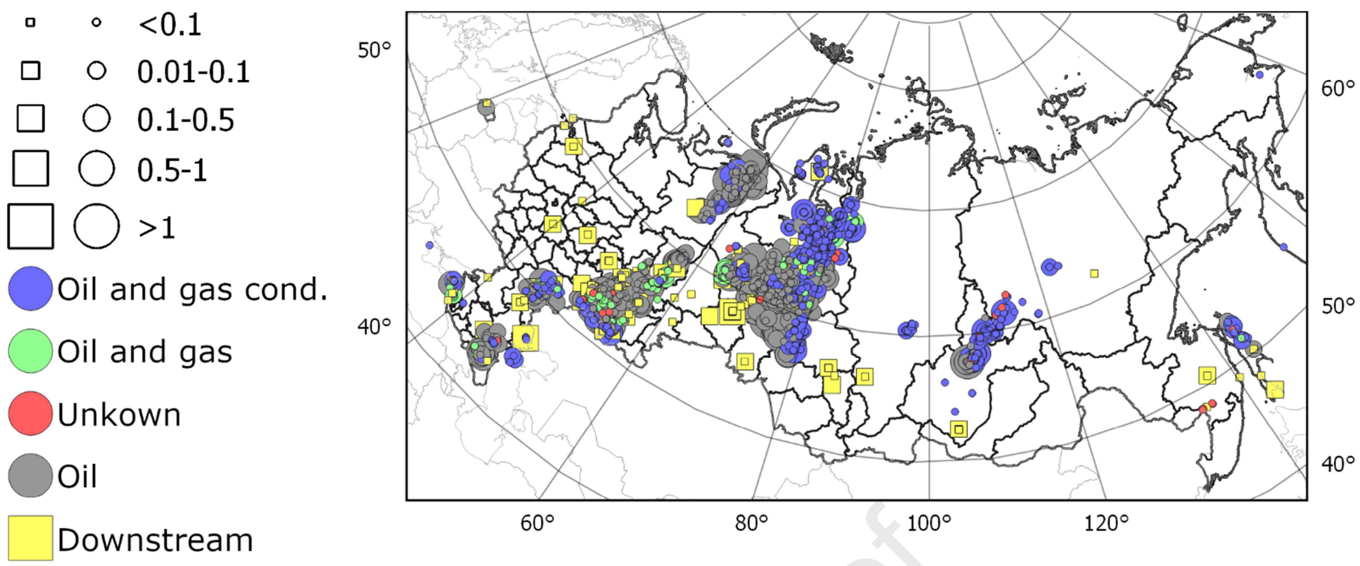


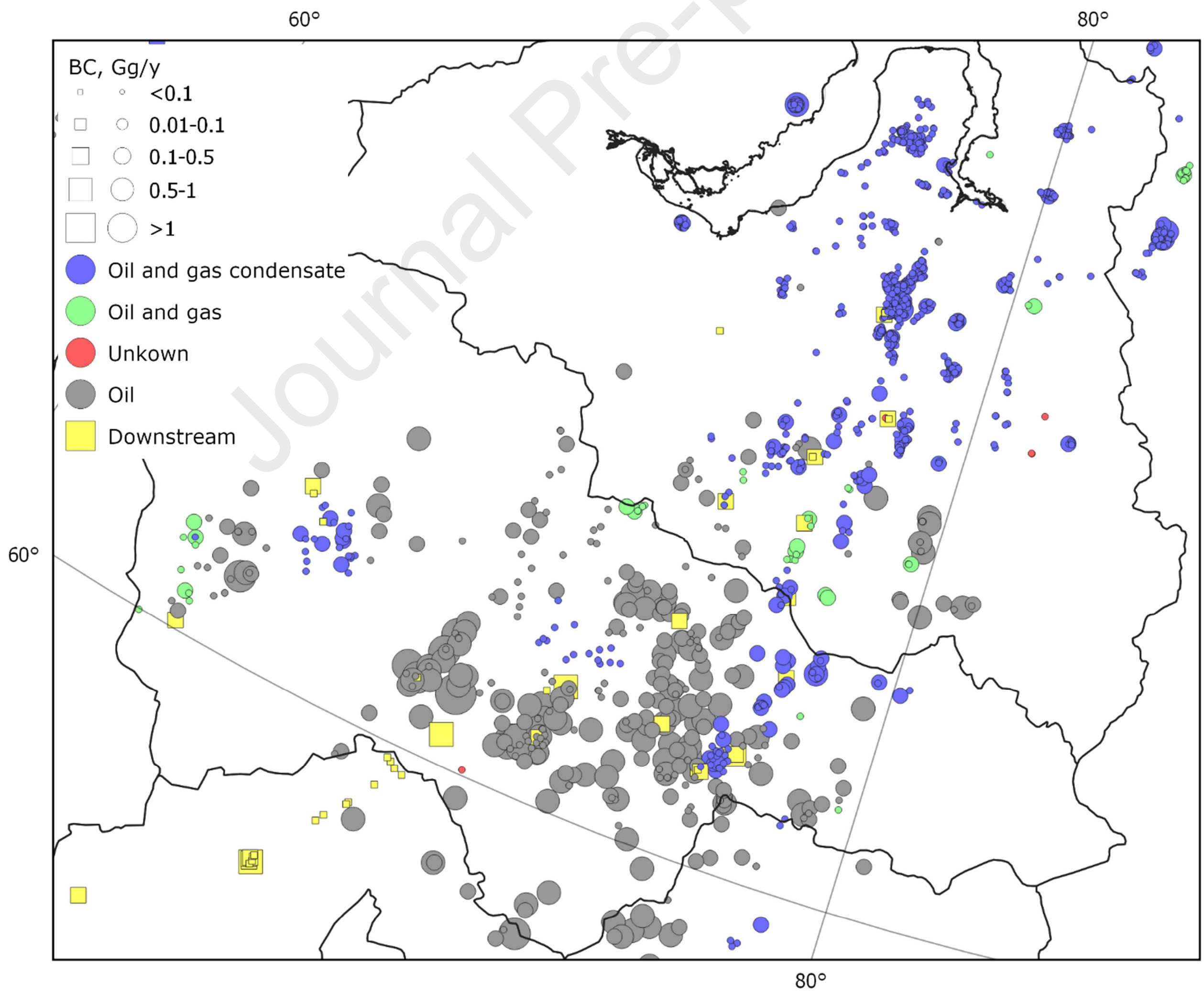
Figure 3. Flaring black carbon emissions in Russia per field type.

Table 3. Uncertainty in black carbon (BC) emissions for the average period 2012- 2017 stemming from the uncertainty in the flared gas volume and emission factors. Overall uncertainty includes both sources of uncertainty.

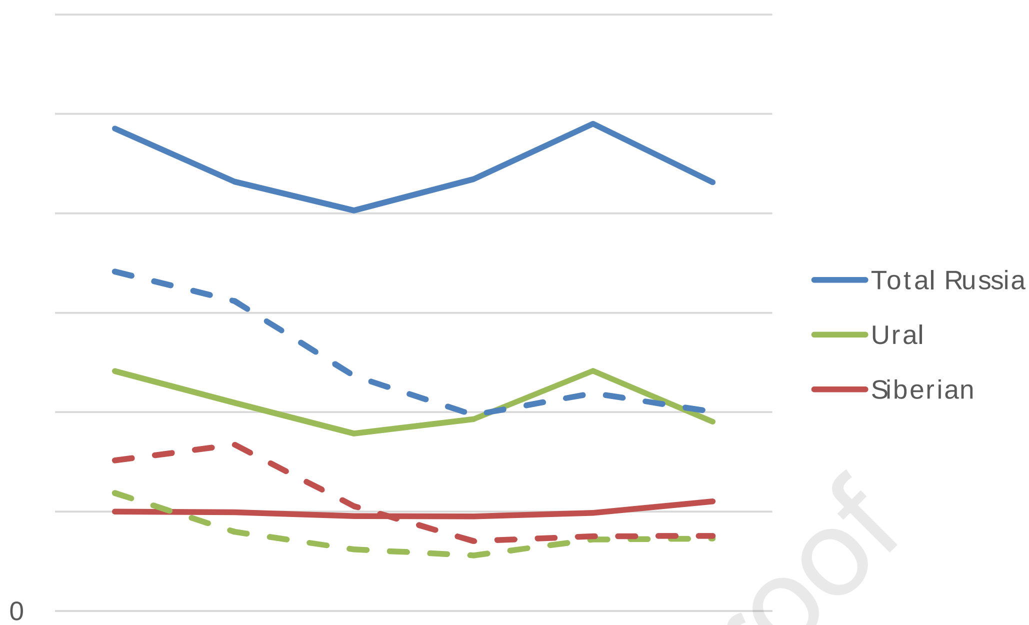
Field type



<0.1
0.01-0.1
0.1-0.5
0.5-1
>1
Oil and gas cond.
Oil and gas
Unkown
Oil
Downstream
50°
40°
60°
50°
40°
60°
80°
100°
120°



60°
80°
BC, Gg/y
<0.1
0.01-0.1
0.1-0.5
0.5-1
>1
Oil and gas condensate
Oil and gas
Unkown
Oil
Downstream
60°
80°



5

Some information on the composition of APG in Russia was nevertheless available. However, most of the data come from the Khanty-Mansiysk Autonomous Okrug in Western Siberia. Thus, other production areas are underrepresented (**Supplementary Materials Table S1**). Spatial and temporal variations in APG composition were found to be high in small areas in other regions (Conrad and Johnson, 2017; Johnson et al., 2013).

In addition, differences in heating values for the subsequent stages of oil and gas separation are even more important. Gas composition data for the different stages from Russia suggest that flaring at stage 3 could multiply BC emissions per BCM by a factor of 5 in oil fields and by a factor of 12 in oil and gas condensate fields (Table 2). The proportions of flaring at the different stages are unknown (CarbonLimits, pers. communication). Huang et al. (2015) and Evans et al. (2017) assumed that the majority of flaring occurs at stage 1. A larger proportion of flaring at the first stage in upstream flares would reduce the BC emissions in our results significantly. For example, when accounting for 70% of flaring at stage 1 and an equal distribution for the later stages, total BC emission estimates would reduce by 23.16 Gg/year or 34% for the period 2012 to 2017. Furthermore, the highest HHV in measurements by Conrad and Johnson was 71.29 MJ/m^3. For the Russian oil fields, the highest HHV for stage 3 APG was 131.02 MJ/m^3. Thus, equation (1) was extrapolated in our analysis. As this extrapolating is taken to far higher HHV than in the experimental data used in Conrad and Johnson (2017), the uncertainty increases with high HHV.

The spatial distribution of emission factors could potentially be further improved based on remote sensing observations. For example, Caseiro et al. (2020) used the satellite-derived flaring temperature as an indicator of the completeness of combustion and as the basis to scale emission factors between flares. Progress on the retrieval of combustion phase of fires from satellite observations was made by Wang et al. (2020) by using the visible energy fraction (the ratio of visible light power to fire radiative power). In their study, the visible energy fraction was correlated with a measure of combustion efficiency from the global fire emission database (https://www.globalfiredata.org/). The retrieval of combustion efficiency of different flares is also one important development direction for the VIIRS Nightfire algorithm.

In our analysis, the uncertainty in the flared gas volume from satellite observation was a minor contributor to the overall uncertainty of BC emissions. Applying the global uncertainty range of the flared gas volume of +/- 9.5% (Elvidge et al., 2016) resulted in an uncertainty range of +/- 6.5 Gg/year in Russia (Table 3). The flared gas volume in 2017 from Sentinel SLSTR by Caseiro et al. (2020) was lower (3.6 BCM or 16.5%, see Table 4) than retrievals from VIIRS Nightfire in 2017 . The differences in the country-aggregated value could mainly be due to a stronger persistency criterion for the detection of flares and less observation opportunities caused by the smaller swath and an earlier overpass time of Sentinel-SLSTR compared to VIIRS (Caseiro et al., 2020). In a comparison of VIIRS Nightfire flared gas volume at offshore sites with government reported data from 9 countries, the accuracy was higher (+/-5%) for aggregated estimates (Brandt, 2020) than the applied uncertainty range in this study. Further work is needed for the accuracy assessment of land-based flare estimates (Brandt, 2020). Currently, the calibration of satellite-observed flared gas volumes against field data from flaring locations is ongoing. Measurements of the flared gas volumes and concurrently observed VIIRS signals from large test flare facilities, such as at the John Zinc testing facility in Oklahoma, could reduce calibration errors and allow better characterisation of the uncertainties of the satellite observations (Zhizhin et al., 2019) in future work.

5 Conclusions

We estimated BC emissions from flaring in Russia for 2012-2017. Our analysis was based on new field-type specific emission factors that were applied to VIIRS observations of the flared gas volume at individual flaring locations. On average for the period 2012 to 2017 the emissions were 68.3 Gg/year, from which 64.1 Gg/year were from upstream (with uncertainty range from 20.98 to 156.53 Gg/year) and 4.2 Gg/year from downstream flares (uncertainty range from 0.33 to 24.93 Gg/year). The major part, 82%, of the emissions came from flares in oil fields. The oil fields comprised only 41% of the total flared gas volume, indicating the importance of field type distinction for flaring emission assessments. Mean annual emission estimates were mostly in line with previous studies. However, our average emission factor was higher than in most other studies, mainly due to applying a new emission factor function and higher heating values for the flared gas in oil fields, making the similarity to some studies coincidental. Emissions showed high interannual variability, with 2012 having the highest BC emission of 81.4 Gg/year and 2017 the lowest with 58.9 Gg/year. Regionally, Khanty-Mansiysk had the highest emissions, representing on average 40% of the total flaring emissions in Russia. While the total emissions had a slight decreasing trend, regional emissions showed more variation. In addition to the new emission estimates, our results show the spatial distribution of the emissions. Taking field type into account was especially important for the spatial distribution, as major emissions were located at oil production fields.

Our results reinforce the importance of flaring in oil and gas extraction as a BC source close to the Arctic. While our results indicate a decreasing trend in the Russian flaring emissions, there remains large potential for emission reduction in the sector. According to our analysis, especially flaring in oil fields and at higher processing stages should be targeted with reduction measures. While our results are based on the latest knowledge from satellite observations and emission factors, significant uncertainties remain associated with the flaring emissions. In order to reduce the uncertainties, emission factors that better represent the actual emissions are needed. This would require measurements of BC emissions at individual flares, detailed gas composition profiles, documentation of different stages of oil and gas separation from fields in Russia and the consideration of the effect of climate conditions on BC emissions.

CRediT authorship contribution

Kristin Böttcher: Conceptualisation, Methodology, Formal analysis, Visualisation, Writing – Original draft, Writing – Review and editing. **Ville-Veikko Paunu**: Conceptualisation, Methodology, Formal analysis, Visualisation, Writing – Original draft, Writing – Review and editing. **Kaarle Kupiainen**: Conceptualisation, Supervision, Writing – Review and editing. **Mikhail Zhizhin**: Methodology, Writing – Review and editing. **Alexey Matveev**: Methodology, Writing - Original draft, Writing – Review and editing. **Mikko Savolahti**, **Zbigniew Klimont**, **Sampsa Väätäinen**, **Heikki Lamberg**: Writing – Review and editing. **Niko Karvosenoja**: Project administration, Funding acquisition, Writing – Review and editing.

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Supplementary material

Table S1: Gas composition (Vol. %), heating values (MJ/m^3) and black carbon emission factors (g/m^3) for associated petroleum gas in Russia.

Figure S1: Mean black carbon emissions from individual flares in Russia for the period 2012-2017.

Figure S2: Yearly black carbon emissions from flaring from Russian regions for the period 2012-2017.

Data availability

Black carbon emissions estimates from flaring in Russia were made available at the Mendeley data repository at the following link: (to be added when published). The published data set contains the coordinates of the flaring locations, the flared gas volume from VIIRS and the estimated black carbon emission for 2012-2017.

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- New estimate for black carbon emissions from flaring in Russia
- Enhanced temporal profiles of flared gas volume from VIIRS
- Oil and gas field-type specific emission factors developed
- Average BC emissions from 2012 to 2017 are estimated at 68.3 Gg/year

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

• The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: